Abstract for International Conference on Computational &
Experimental Engineering and Sciences (ICCES'08)
Honolulu, Hawaii

Modeling Creep Effects within SiC/SiC Turbine Components

J. DiCarlo and J. Lang
Structures and Materials Division
NASA Glenn Research Center, Cleveland, OH

Anticipating the implementation of advanced SiC/SiC ceramic composites into the hot section components of future gas turbine engines, the primary objective of this on-going study is to develop physics-based analytical and finite-element modeling tools to predict the effects of constituent creep on SiC/SiC component service life. A second objective is to understand how to possibly select and manipulate constituent materials, processes, and geometries in order to minimize these effects. In initial studies aimed at SiC/SiC components experiencing through-thickness stress gradients, creep models were developed that allowed an understanding of detrimental residual stress effects that can develop globally within the component walls. It was assumed that the SiC/SiC composites behaved as isotropic visco-elastic materials with temperature-dependent creep behavior as experimentally measured in-plane in the fiber direction of advanced thin-walled 2D SiC/SiC panels. The creep models and their key results are discussed assuming state-of-the-art SiC/SiC materials within a simple cylindrical thin-walled tubular structure, which is currently being employed to model creep-related effects for turbine airfoil leading edges subjected to through-thickness thermal stress gradients. Improvements in the creep models are also presented which focus on constituent behavior with more realistic non-linear stress dependencies in order to predict such key creep-related SiC/SiC properties as time-dependent matrix stress, constituent creep and content effects on composite creep rates and rupture times, and stresses on fiber and matrix during and after creep.

Modeling Creep Effects within SiC/SiC Turbine Components

J.A. DiCarlo and J. Lang
Structures and Materials Division
NASA Glenn Research Center
Cleveland, Ohio

Research Supported by the
NASA Fundamental Aeronautics: Supersonics Project

Presented at ICCES-08
March 19, 2008, Honolulu

Background

Under the new NASA Fundamental Aeronautics Program, one of the objectives within the Supersonics Project is to develop physics-based tools and concepts that will allow advanced SiC/SiC CMC systems to be implemented in the hot turbine section of future aero-propulsion engines.

Mechanistic and computational modeling studies are now on-going at NASA Glenn
(1) to develop advanced design tools to down-select and improve the constituent materials, processes, and fiber architectures for SiC/SiC turbine components; and
(2) to develop advanced lifing tools that address the multiple service conditions of these components.

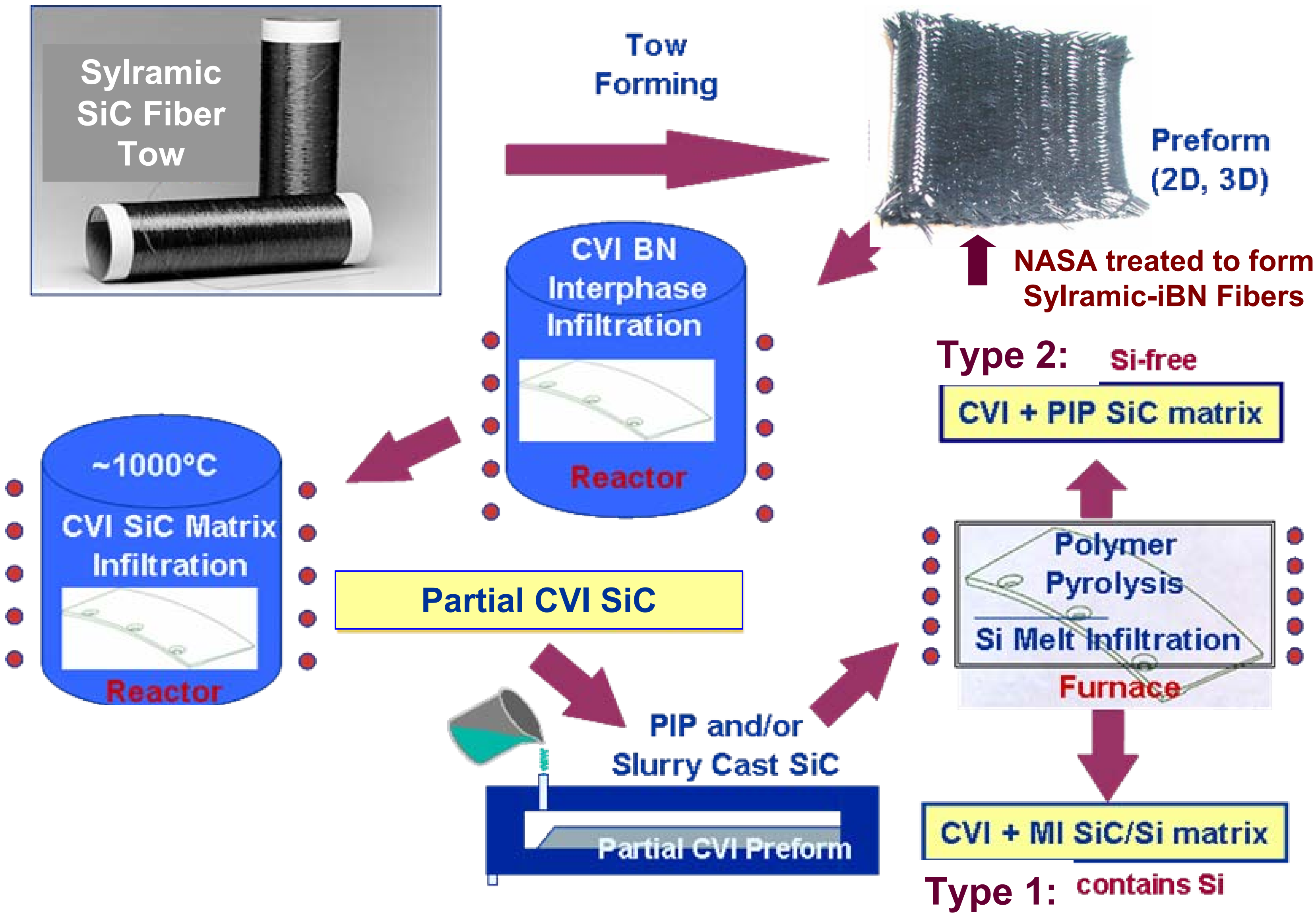
Creep Concerns with SiC/SiC Component Lifing

- ***Dimensional changes***: Should not be very important because SiC/SiC will currently fail at creep stains < 1%.
- ***Constituent Rupture***: As with monolithic ceramics, creep implies flaw growth and time-dependent weakening of the fiber and matrix, currently leading to SiC/SiC rupture at creep strains of ~0.4%.
- ***Internal Environmental Attack***: At stresses above matrix cracking, SiC/SiC creep can increase crack openings, leading to enhanced internal attack of all constituents and shorter life.
- ***Residual Stress Development***:
  - At SiC/SiC stresses below matrix cracking, differences in fiber and matrix creep behavior can put matrix in internal tension with time, resulting in reduction of matrix cracking stress and a higher risk of shorter life due to internal environmental attack.
  - Residual stress is a particular concern for components with stress and thermal gradients, such as internally cooled turbine airfoils.
  - ***Adverse effects can occur as low as 0.05% creep strain***.

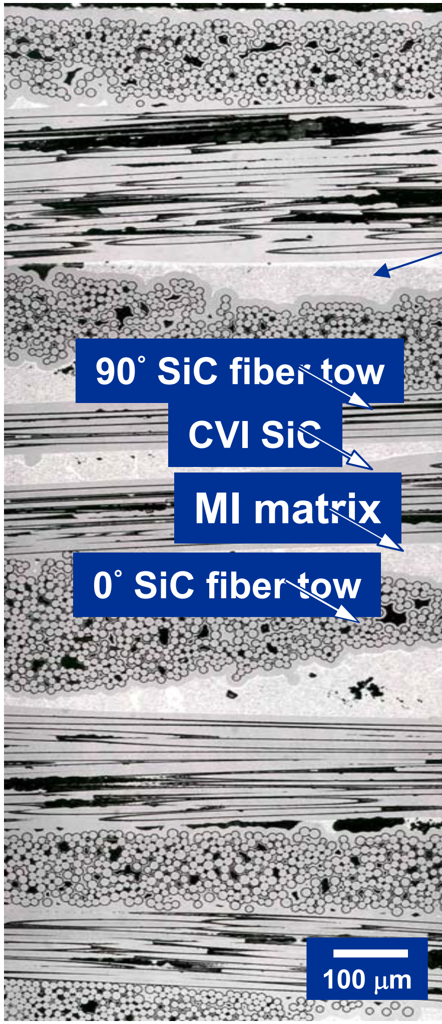
Objectives/Outline

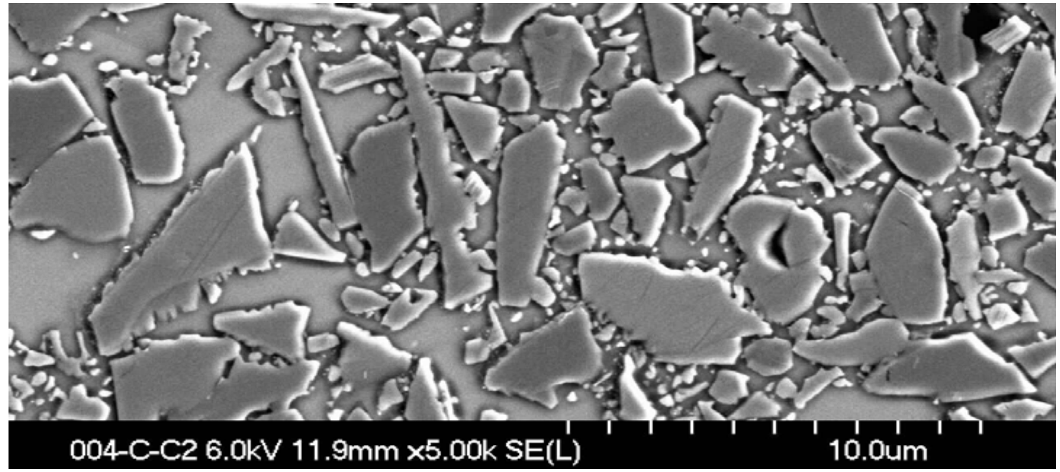
- Briefly review the processing approaches, complex microstructures, and performance status of advanced SiC/SiC composite materials currently being developed at NASA for supersonic engines.
- Present some initial creep models under recent study at NASA to predict creep effects in these SiC/SiC materials at stresses *below the onset of matrix cracking.*
- Discuss some design results from these models and how they need to be further improved to better account for the underlying creep mechanisms.

NASA Processes for High Temperature SiC/SiC Components

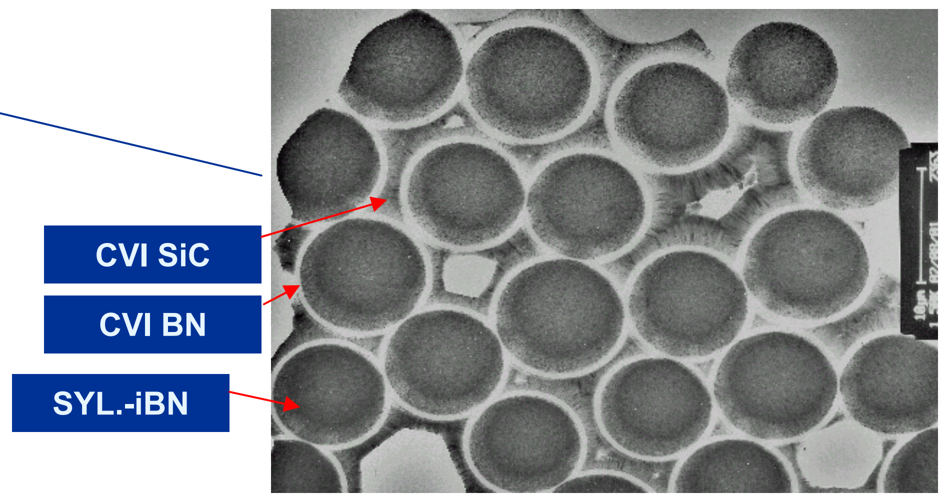


Advanced SiC/SiC Composite Microstructures are Complex



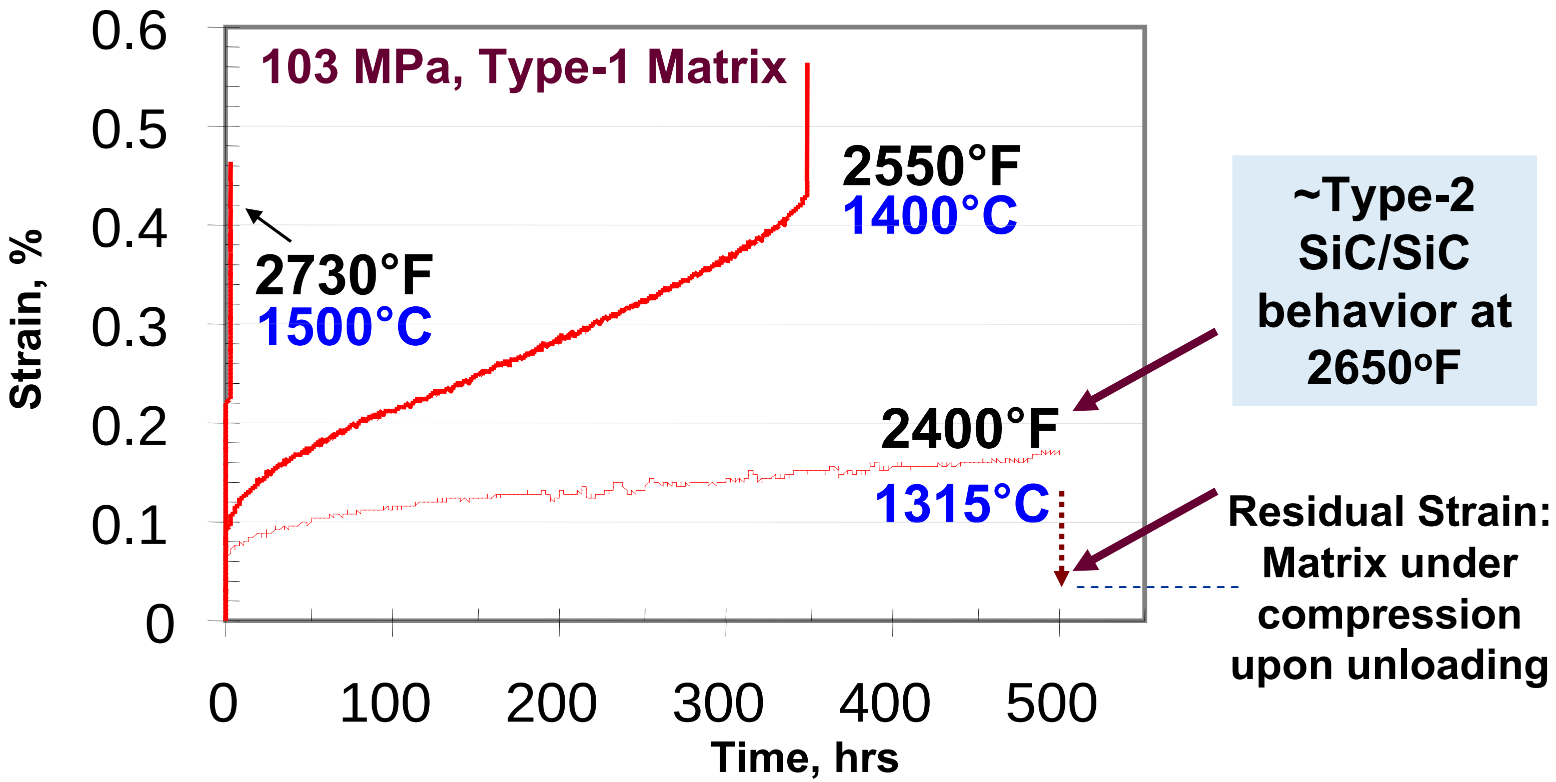


SiC particulates and silicon within Type-1 CVI+MI matrix



Sylramic-iBN SiC fibers within a tow

Typical SiC/SiC Data for Initial Tensile Creep Models: Constant Temperature, Constant Stress Results for On-Axis Creep of 2D-woven 0/90-balanced thin-Walled Panels



Computational Creep Models must account for composite elastic, primary, and steady-state secondary creep regions, plus residual compression stress on matrix

Approach for SiC/SiC Creep Model Development

- Begin with simplest models to better confirm underlying mechanisms. Move to higher fidelity models only when needed.
- Primary goals are first to understand major effects of composite creep in components and then to develop approaches that can mitigate the adverse effects.
  - **1D Continuum Model**: Fit panel tensile on-axis creep curves to general analytical equation, assuming symmetric and linear stress dependencies
  - **1D Constitutive Model** : Fit panel tensile on-axis creep curves to general two constituent equation based on measured non-linear fiber behavior and a continuum matrix model
  - **Higher Fidelity Constitutive Models**:
    - Multiple constituents
    - Asymmetric behavior (compressive creep ≤ tensile)
    - 2D and 3D models to account for fiber architecture effects
    - Finite Element models for SiC/SiC component designers

Initial 1D Continuum Creep Model

- Assumes SiC/SiC composite is a **homogeneous isotropic material** with elastic, anelastic, and viscous (non-recoverable) strain components that are linear and symmetric with tension and compressive stresses
- **Analytical Model**: Total creep strain vs. time given by

$$\boxed{e(t) / e(0) = 1 + A [1- \exp- t/\tau(T)] + A\, t/8\tau(T)}$$

A = system-dependent creep parameter

τ = temperature-dependent constant

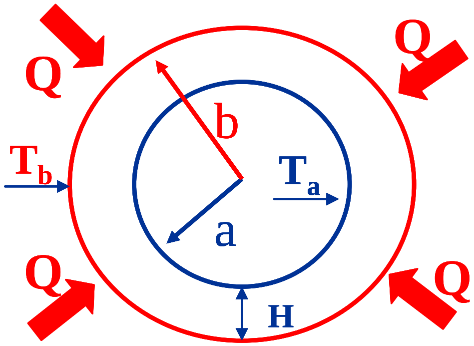
- **FE Model**: Stress Relaxation vs. time given by 4-parameter 2-term Prony Series

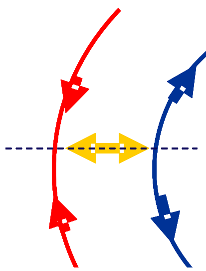
$$\boxed{G(t)/G(0) = 0.30 \exp(- t/C) + 0.70 \exp (- t/D)}$$

- Constants A, C, D, and τ empirically determined from on-axis creep data for advanced SiC/SiC systems from 1200 -1450^{o}C at stresses below matrix cracking

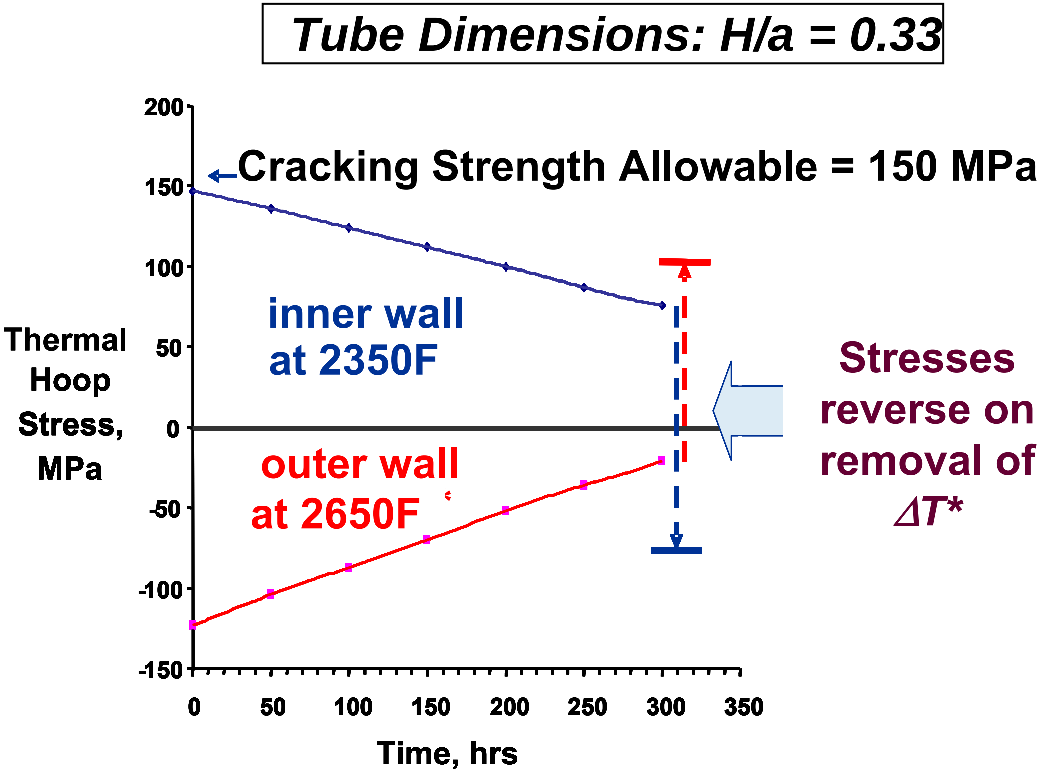
1D Continuum Model Applied to Cooled Tube:

*Hoop Stress Relaxation for Type-2 SiC/SiC at ΔT*max = 300°F*





- Tensile hoop on cold inner wall
- Tensile radial near wall center
- Compressive hoop on hot outer wall



Both Inner and Outer Wall stresses relax with time, thereby increasing material reliability at temperature. But Outer Wall <u>goes into tension</u> on ΔT* removal (e.g., during component cool-down). <u>Outer wall residual tension adversely increases with time at temperature</u>.

1D Two-Constituent Creep Model

Key Need:

1D continuum model does not allow monitoring of matrix stress throughout component life, which needs to be kept at low levels in order to minimize risk of cracking and internal environmental attack

Constituent Approach:

- Although convenient, <u>remove the assumption of linearity</u> since much data exists that show the SiC fiber and matrix constituents display both primary and secondary creep strains that are non-linear with stress: $\mathbf{e = \sigma / E + \sigma \alpha [1 - \exp - t/\tau(T)] + \sigma^n \beta(T) t}$
  - constituent viscous-strain stress exponent **n** can be > 1
  - α, τ are the constituent anelastic parameters
  - $\beta = \beta_o \exp(-B/T)$ are the constituent viscous parameters
- Develop approaches that measure the constituent creep parameters either directly from constituent creep measurements or indirectly from SiC/SiC creep curves

Current Methods for Determining Constituent Creep Parameters for Two-Constituent Model

SiC Fibers:

Using in-house tests and literature data measured on straight fibers and multi-fiber tows, NASA has determined the following best-fit creep parameters for the Sylramic-iBN SiC fiber:

	E_f	n_f	α_f	β_{fo}	B_f
Sylramic-iBN	**350 GPa**	**3**	**0.6**	**13 x 10 ^{6} MPa^{-3}**	**86000 K**

SiC Matrices:

- Since high-performance SiC matrices typically have complex microstructures that are not reproducible as monolithics, it is assumed that the matrix acts as a continuum material.
- Best-fit creep parameters for this effective matrix were then determined using composite creep theory, the measured fiber creep parameters, and data from constant stress creep tests on relevant composites.

Method for Determining Matrix Creep Parameters

- For a given SiC/SiC on-axis creep curve at constant stress σ_c below matrix cracking, it is assumed fiber, matrix, and composite creep strain and creep rates are the same at any given time

- It is also assumed when a composite steady-state creep rate $\acute{e}_{ss}$ is reached, the fiber and matrix have reached their equilibrium stresses, so that the ***Fiber Stress at Steady State*** $\sigma_f(\infty)$ can be determined from NASA-measured viscous parameters n_f and β_f for the fiber: $\sigma_f(\infty)^{n_f} = \acute{e}_{ss} / \beta_f$

- ***Matrix Stress at Steady State*** $\sigma_m(\infty)$ can then be calculated from

$$\sigma_m(\infty) = [\, \sigma_c - V_f\, \sigma_f(\infty)\,] / V_m$$

and β_m, n_m **from** $\beta_m = \acute{e}_{ss} / \sigma_m(\infty)^{n_m}$

where $\acute{e}_{ss}$ is measured at multiple composite stresses.

Initial Analysis of On-Axis SiC/SiC Creep Behavior

Using limited tensile creep data at stresses below matrix cracking for the NASA Type -1 and Type -2 SiC/SiC, initial analyses shows the following **matrix** viscous creep parameters for $V_f \sim 0.2$ and CMC stresses up to 150 MPa:

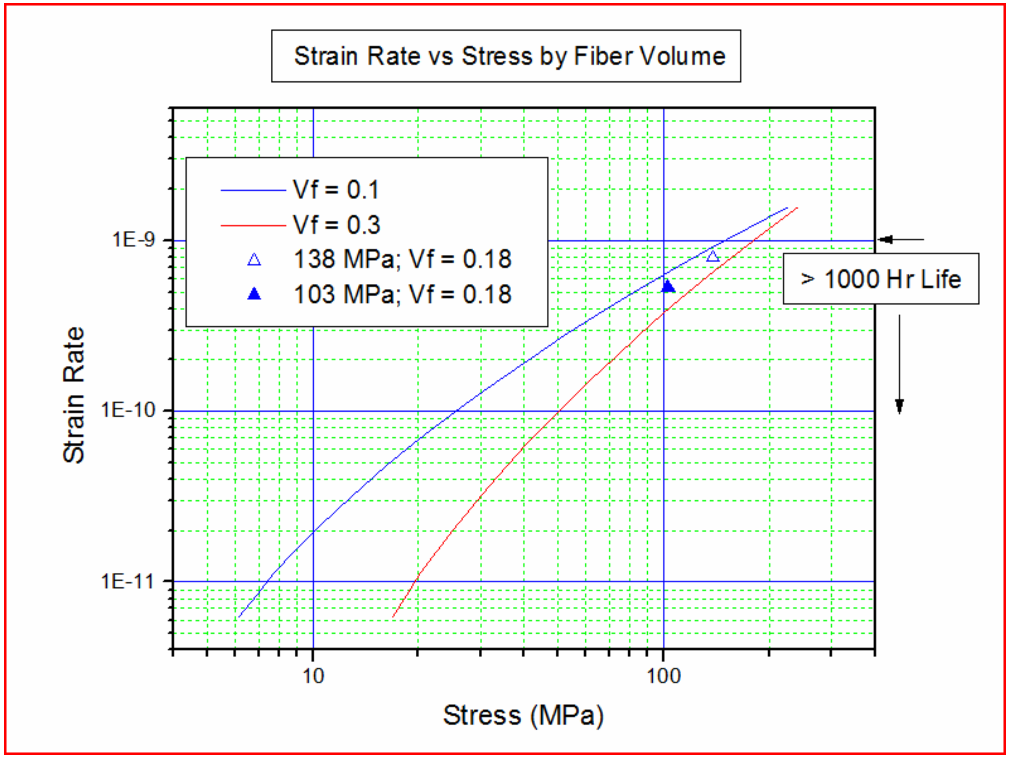
	E_m	n_m	β_m (2400F)	Fiber Stress	Matrix stress
Type - 1	**180 GPA**	**1**	7.5×10^{-12} MPa^{-1}	↑ with time	↓ with time
Type - 2	**180 GPA**	**1**	2.7×10^{-12} MPa^{-1}	↓ with time	↑ with time

Matrix parameters are consistent with similar monolithics and across CMC tensile creep data from 70 to 150 MPa and from 1200 to 1450°C

- ***NASA Type-1 SiC/SiC tensile data with Si-containing SiC matrix indicate matrix creep > Sylramic-iBN fiber creep, which in time will result in increase in cracking strength after creep as has been observed.***
- ***NASA Type-2 SiC/SiC tensile data with purer SiC matrix indicate matrix creep < Sylramic-iBN fiber creep so that matrix is adversely gaining stress during tensile creep.***

SiC/SiC Creep and Life Prediction Using Two-Constituent Model

Type-1 SiC/SiC at 2400°F (1315°C)



- ***With increasing composite stress, steady-state creep rate for Type-1 SiC/SiC should display a constantly decreasing stress exponent.***
- ***Composite rupture life should be predictable from creep rate using Monkmann-Grant relation:*** $t_R = C/ \acute{e}_{ss}^{m}$.

Summary and Future Work

Current NASA SiC/SiC creep modeling efforts are showing that

- **For those components with stress gradients (for example, due to thermal gradients), the simple 1D continuum model shows that creep effects can lead to adverse build up of residual stress that can increase the risk of matrix cracking and reduced life due to internal environmental attack.**
- **However, to better quantify these effects, SiC/SiC constitutive creep models need to be developed to better predict the local stress on the matrix in various locations in the component.**
- **Using empirical SiC fiber and SiC/SiC composite creep data, the 1D two- constituent model generally shows that the stress on the Si-rich Type-1 matrix will decrease or increase with time depending whether local stress is tensile or compressive, respectively. For Type-2 SiC/SiC with pure SiC matrix, opposite behavior should be expected.**
- **Although convenient for simple design predictions, future work will need to expand 1D two-constituent creep model in terms of multiple constituents, multiple geometries of the constituents, and multiple directions for the local component stresses.**